(12) UK Patent Application (19) GB (11) 2 090 407 A

(54) **F-K filtering of multiple reflections from a seismic section**

(57) Multiple reflections are filtered from seismograms by transforming the seismograms at 34, 35 into an f-k array representing amplitude as a function of frequency and wave number. The inverse of the f-k transform of the multiple reflections is generated at 18-31 and the f-k array of the seismograms is filtered at 32, 33 by weighting all samples with the inverse of the f-k transform of the multiple reflections.
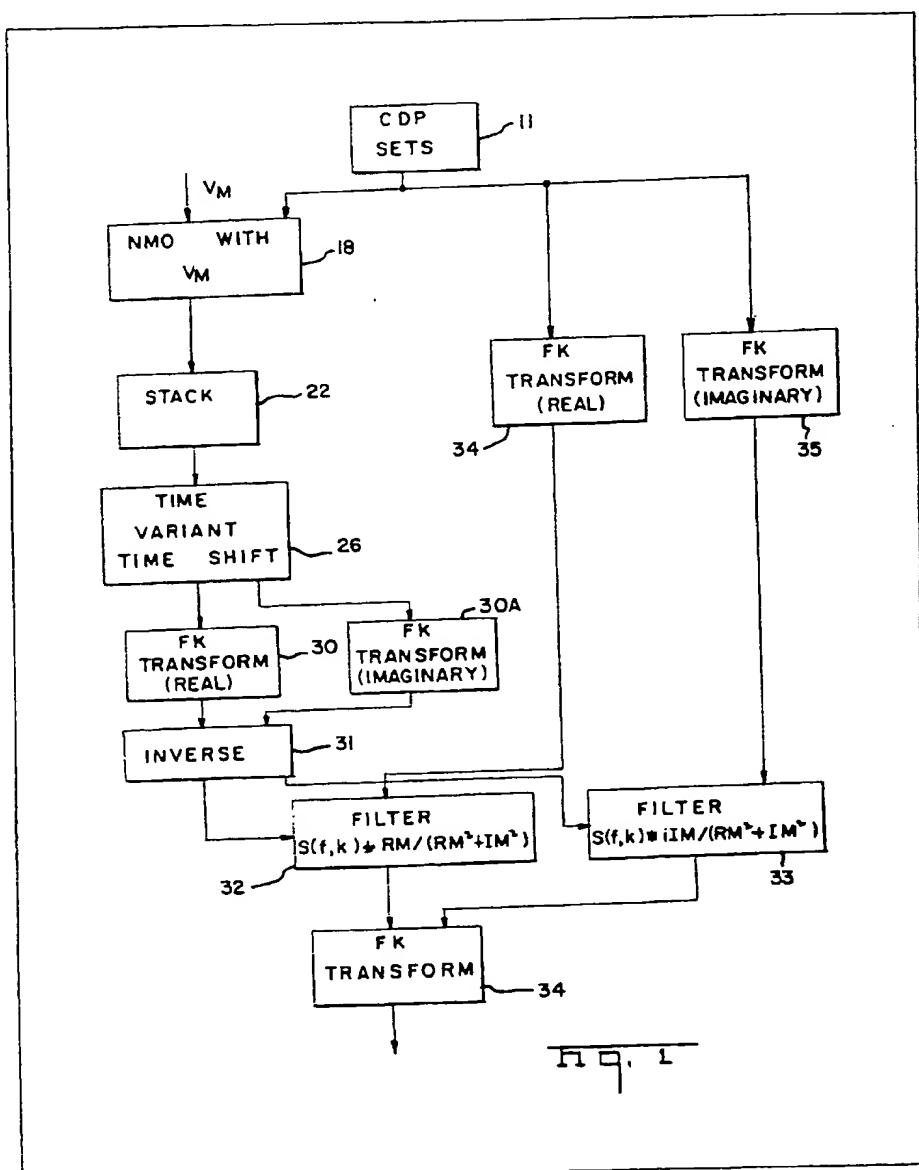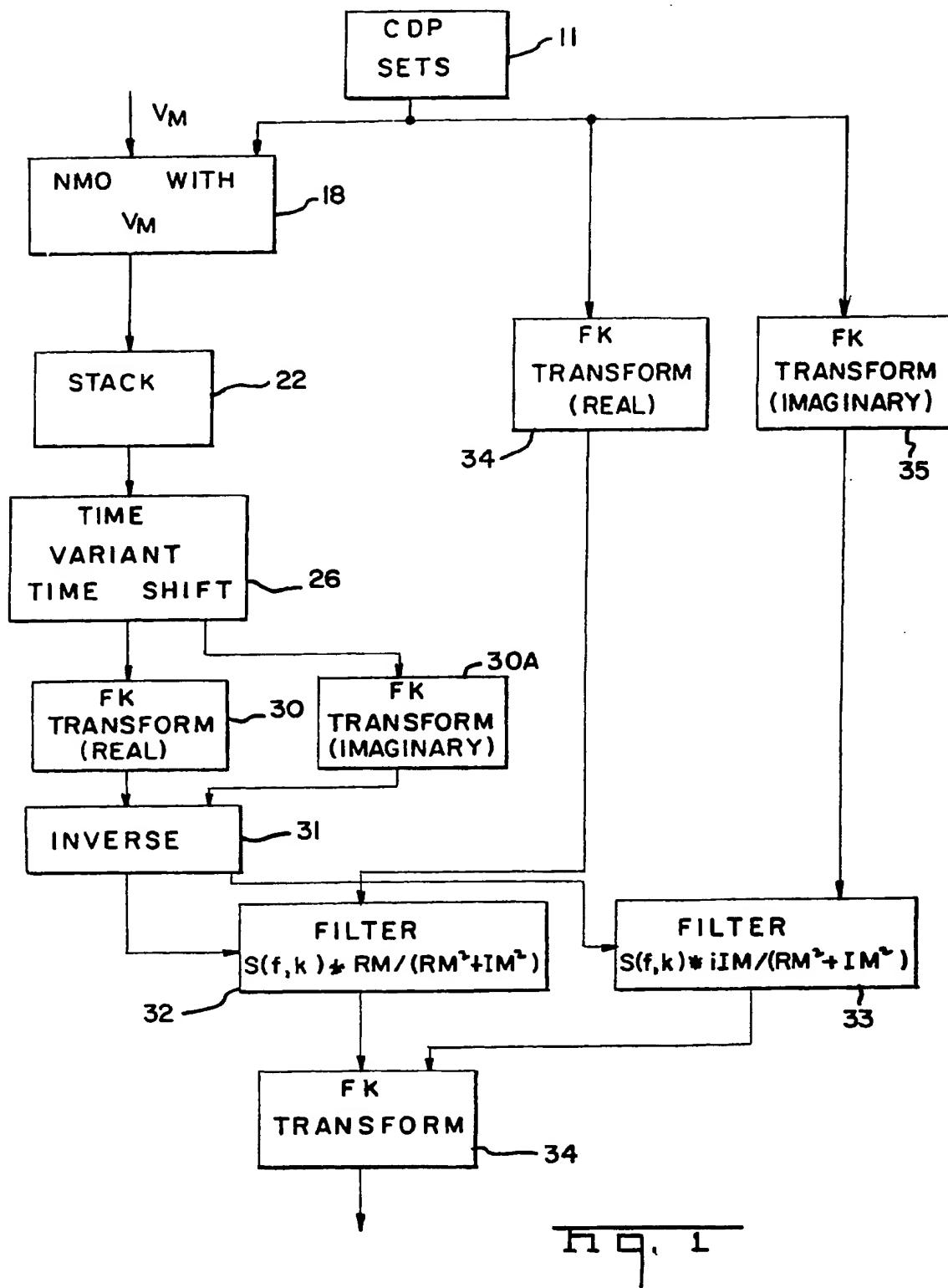
Fig. 1

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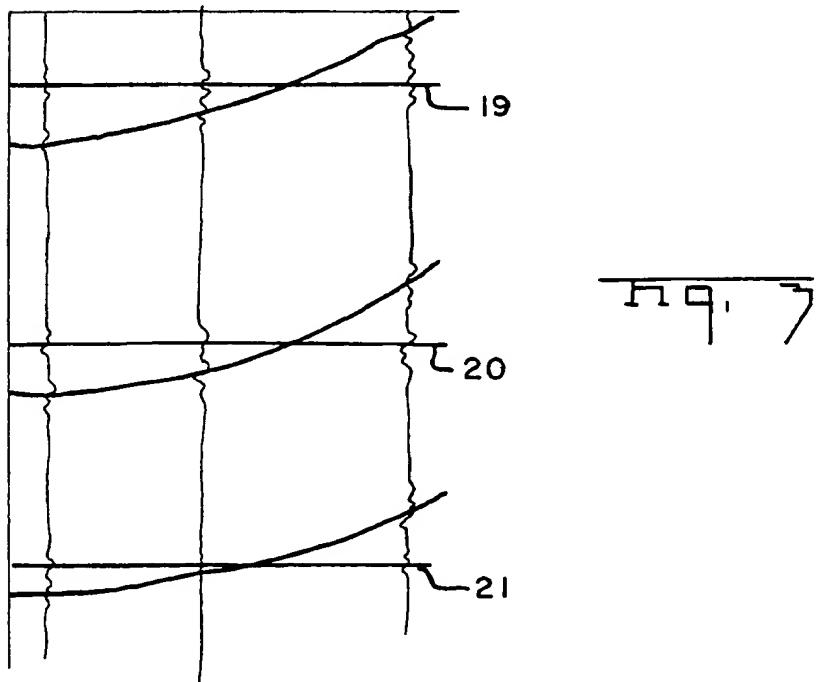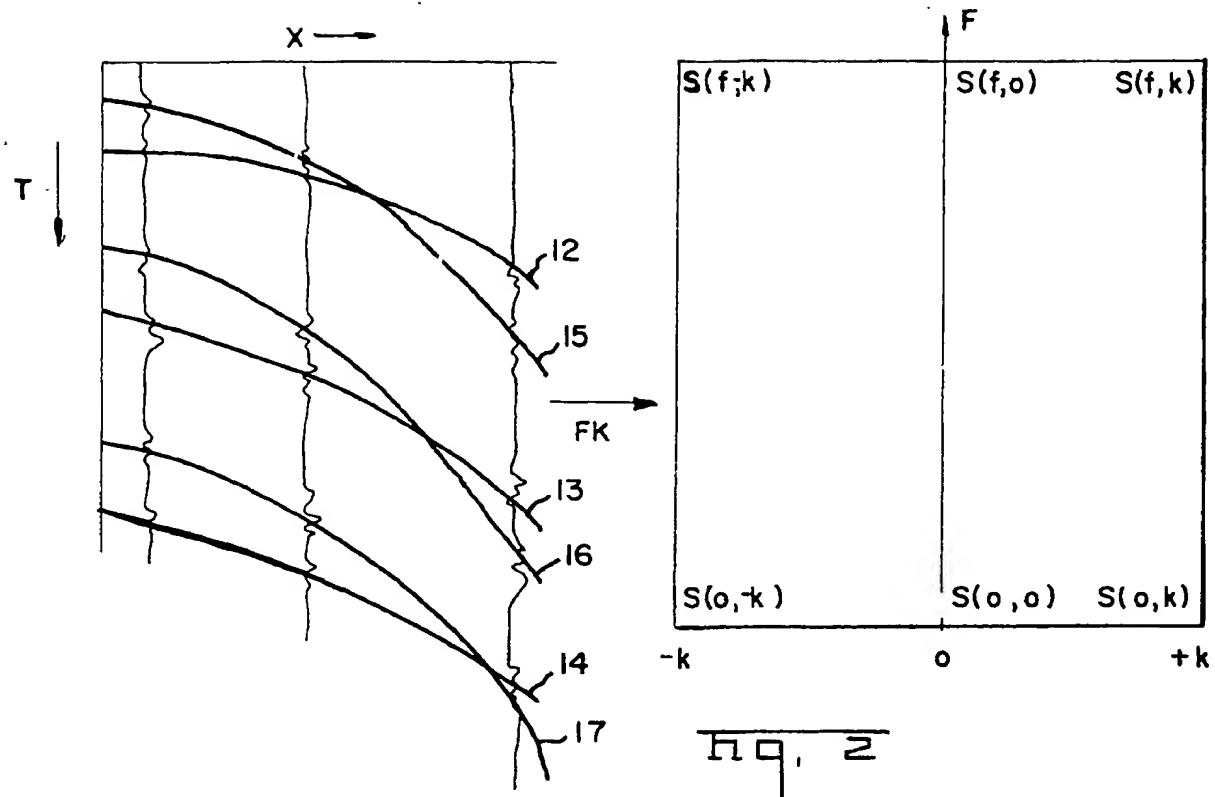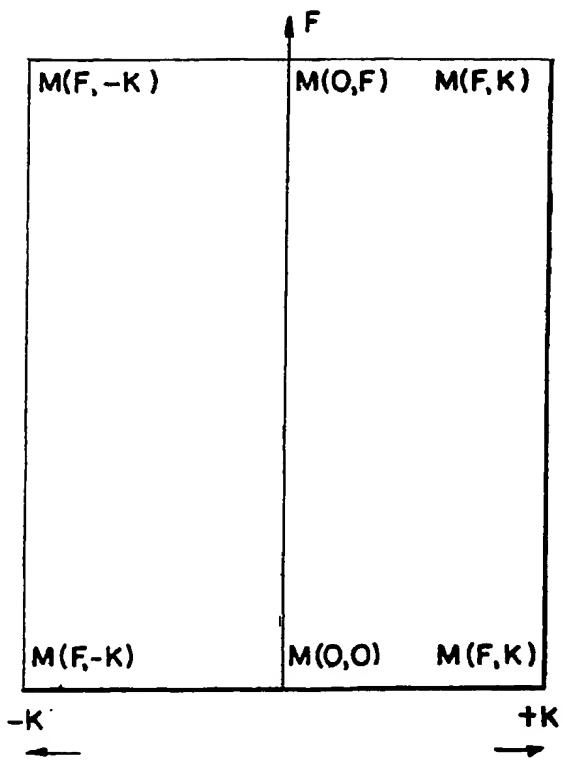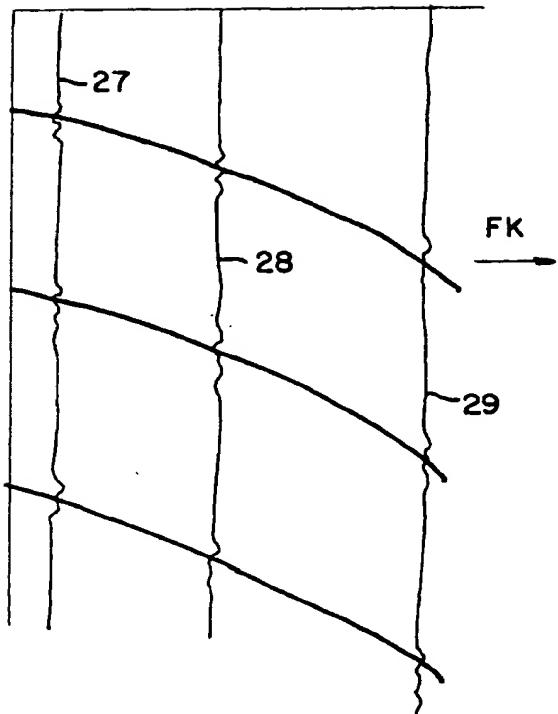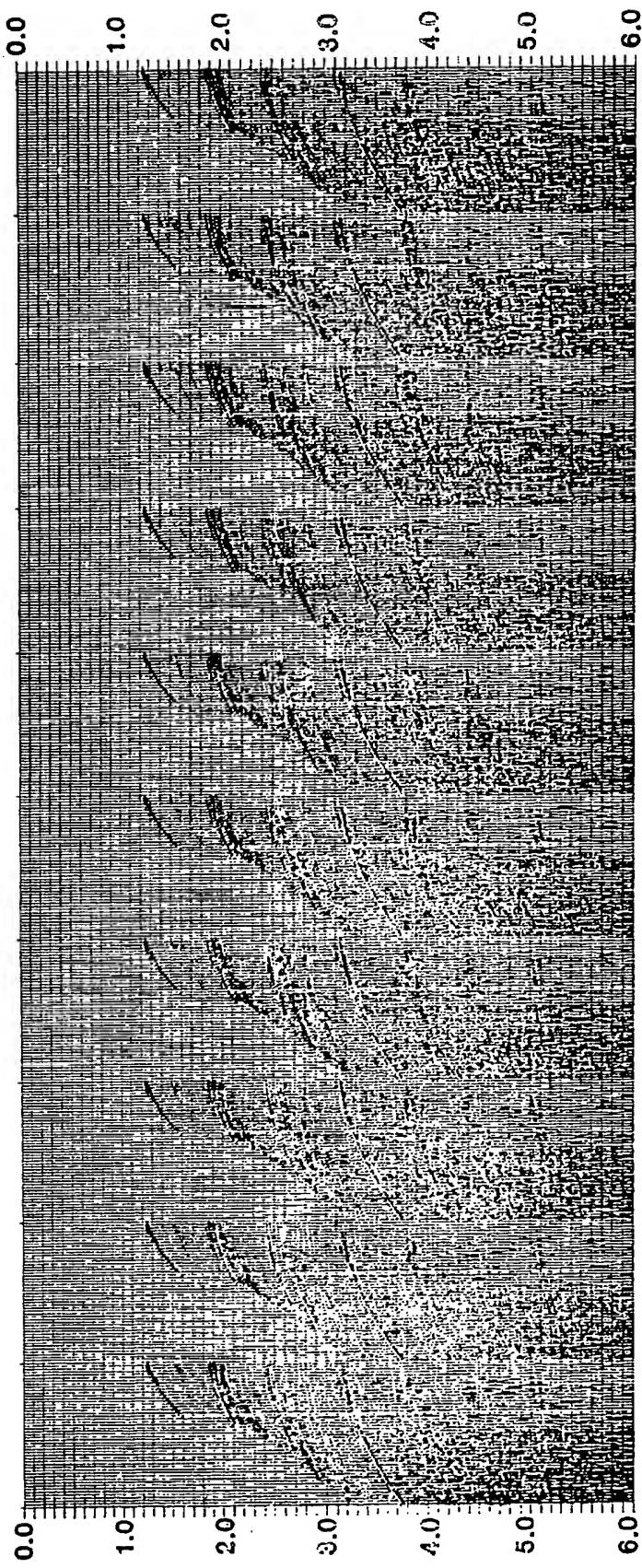
Fig. 1

Fig. 2

Fig. 3

Fig. 4

FK →

27

28

29

M(F,−K)   M(O,F)   M(F,K)

F

M(F,−K)   M(O,O)   M(F,K)

−K   +K

Fig. 5

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Fig. 6

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Fig. 7

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Fig. 6

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fig. 9

NORMAL STACK
RN 4 RN 3 RN 2 RN 1
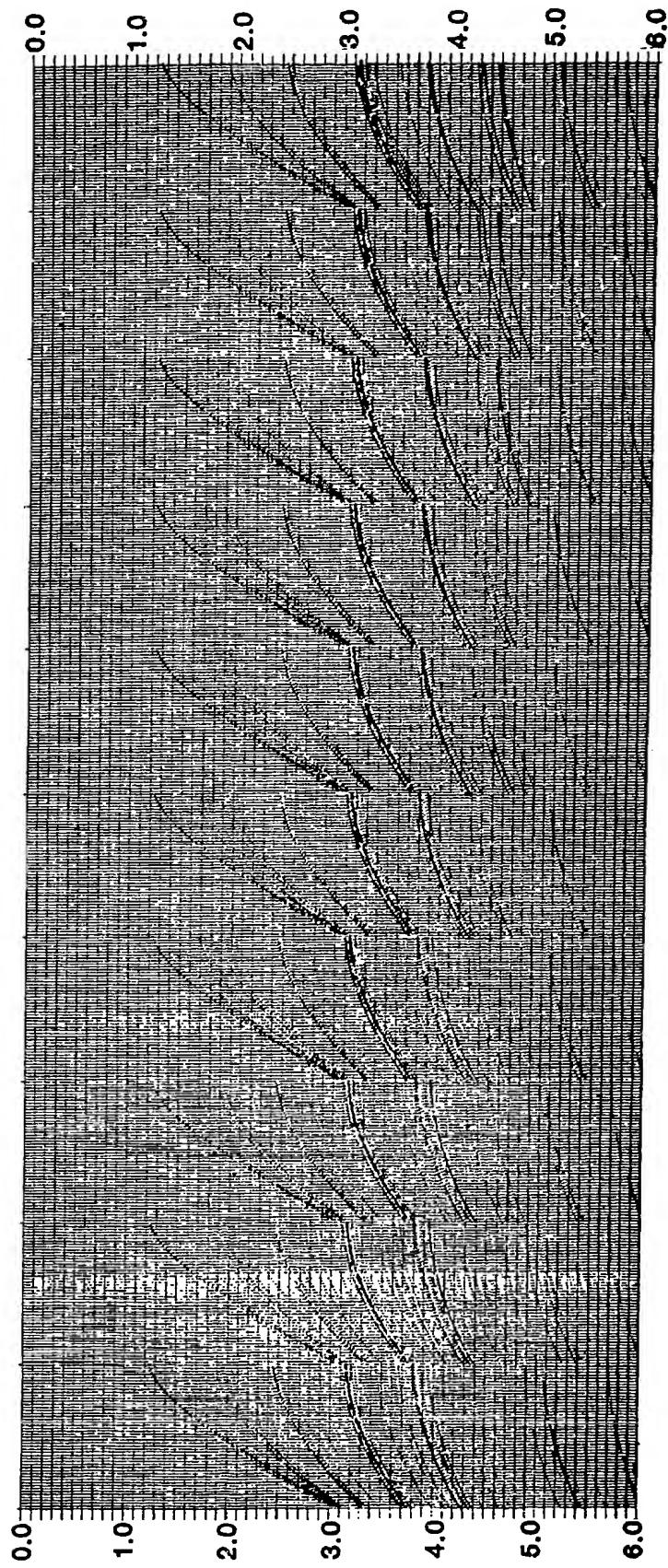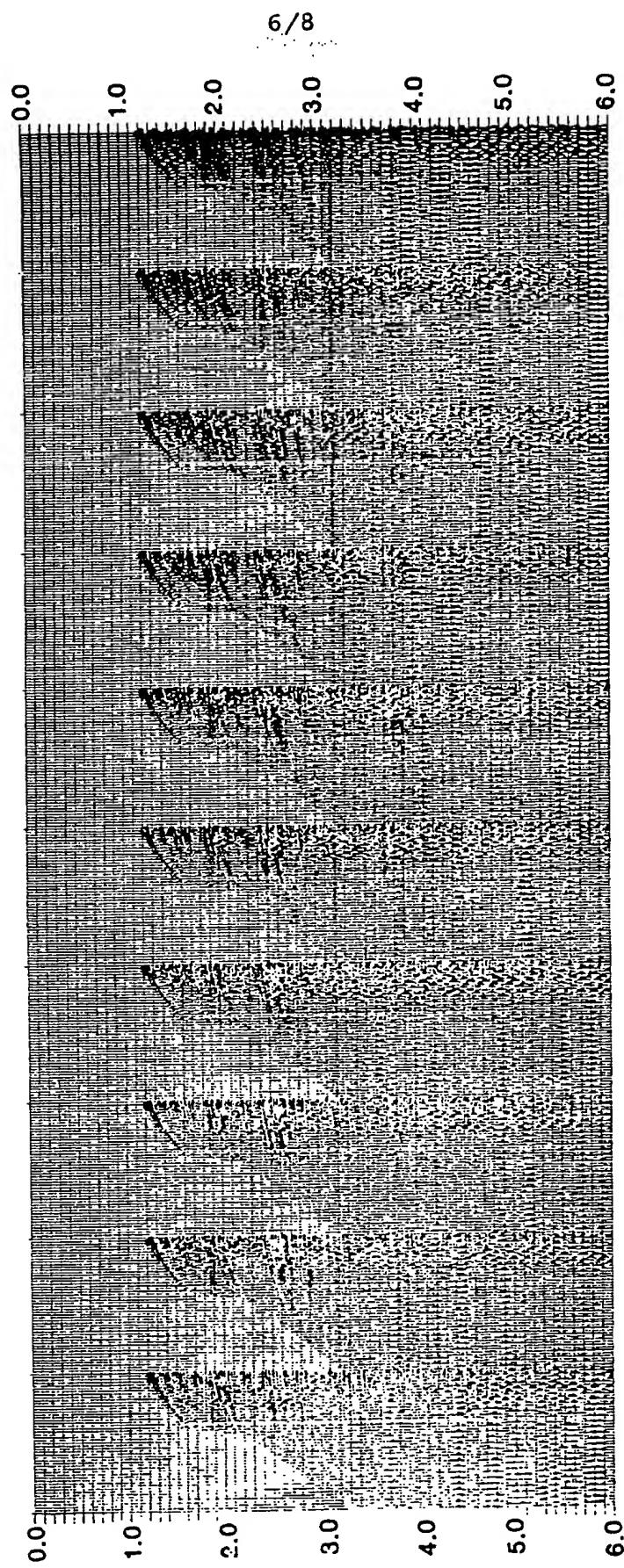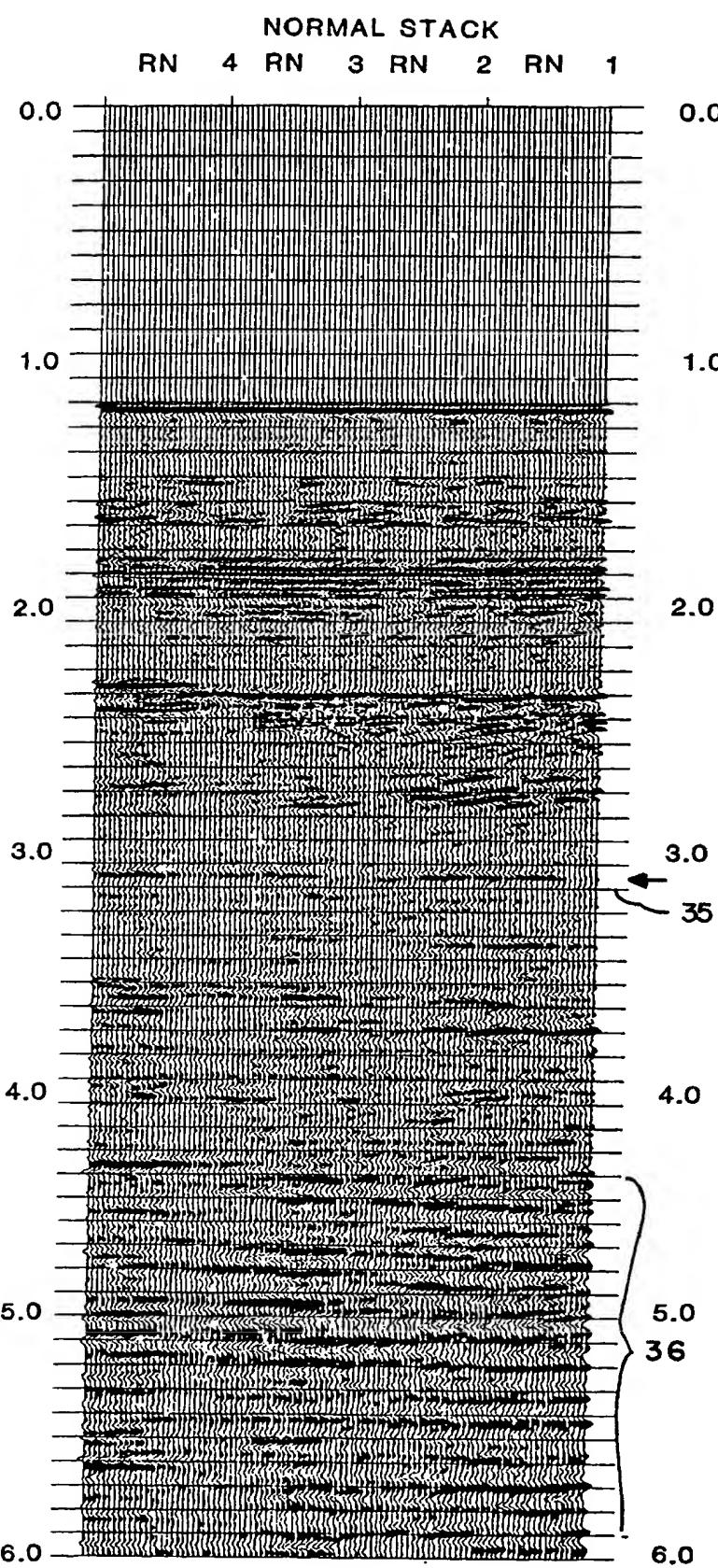
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FK STACK

fig. 10

RN 4 RN 3 RN 2 RN 1
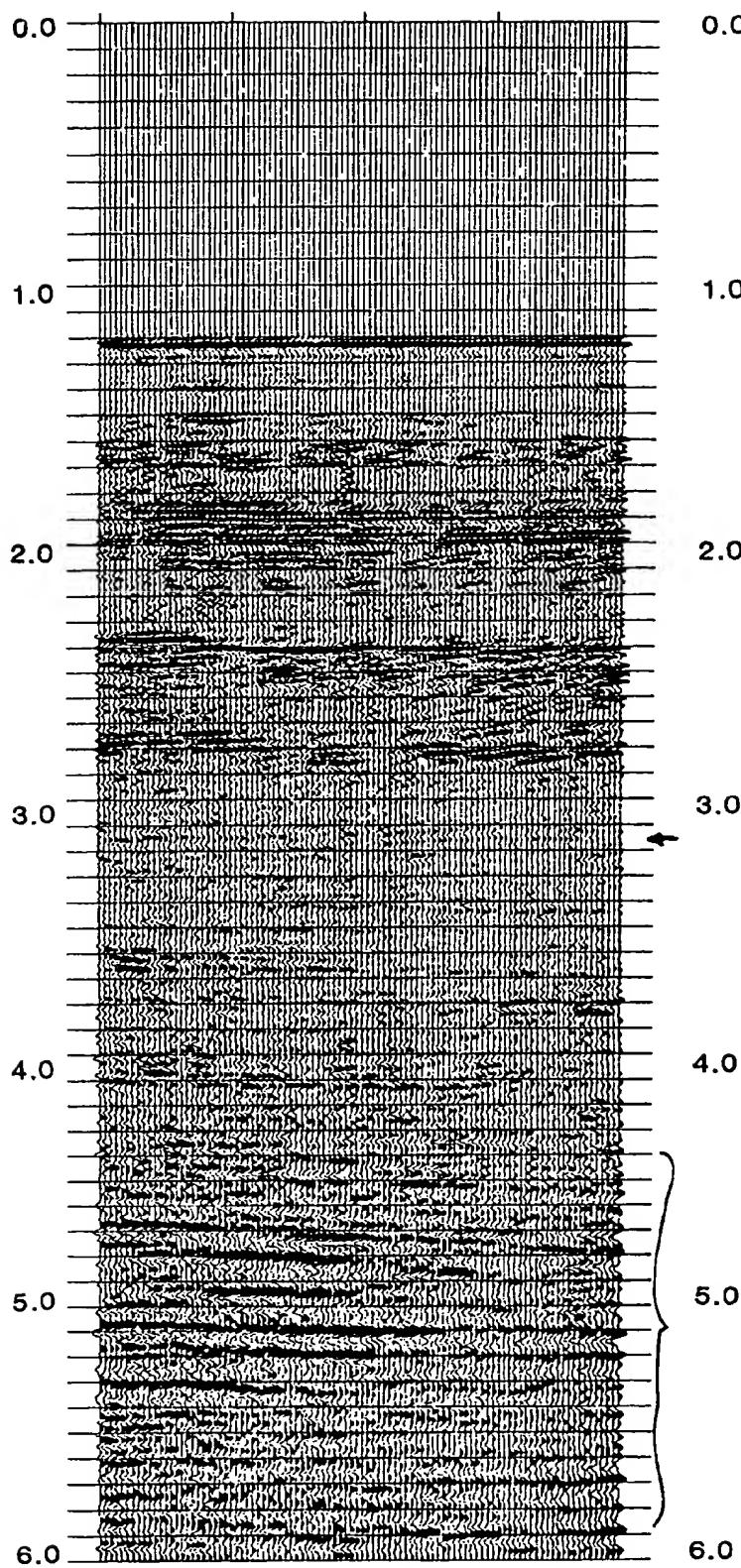
SPECIFICATION

F-K filtering of multiple reflections from a seismic section

5

This invention relates to geophysical exploration and more particularly to the filtering of multiple reflections from a seismic section.

A seismic section is a set of seismograms which
10 depicts the subsurface layering of a section of the earth. Before an array of seismic samples can be converted into a seismic section which can be interpreted by the geophysicist, the seismograms must be procesed to remove noise. One of the most
15 frequently occurring types of noise arises from multiple reflections of the seismic energy between reflecting layers in the earth.

Various processes have been devised for suppressing multiple reflections. In one such process, multi-
20 ple seismic coverage is obtained and stacked to suppress the multiple reflections. Various names have been given to the general process of obtaining multiple seismic coverage, e.g., common depth point techniques, common reflection point techni-
25 ques, and roll-along techniques. All these techniques involve the general principle of recording multiple seismic data from the same reflection point in the subsurface by employing variable horizontal spacing between a seismic source and seismic detector.
30 These techniques are applicable to both marine and land seismic work. A description of such techniques is given by Lorenz Shock in an article entitled "Roll-Along and Drop-Along Seismic Techniques", published in GEOPHYSICS, Vol. XXVIII, No. 5, Part II,
35 pp. 831-841, October, 1963. The data are corrected for normal moveout and statics and are then stacked.

Common depth point seismic techniques are generally credited with producing better seismic
40 data than those techniques which produced single-fold seismic data. In stacking the common depth point seismic data, the primary reflections are essentially in phase and thus are added whereas the distortions such as multiple reflections are out of
45 phase and tend to be cancelled. Thus the multiple reflections are suppressed and the primary reflections are enhanced.

The seismic arrays produced by these methods are generally X-T arrays in which the amplitude of
50 the seismic reflections is plotted as a function of record time (T) and distance (X). These arrays may be transformed into f-k arrays which represent amplitude as a function of frequency and wave number.
55 In our co-pending patent application No. 8125268 (Mobil Case F-0343) we have described a method for obtaining an improved representation of the subsurface layering by filtering the f-k transform. The filtering is carried out on digitized samples by
60 weighting the samples in closed regions of frequency and wave number with a weighting dependent upon the signal and the noise.

We have now found that f-k filtering may be used to suppress multiples by weighting all the samples
65 in the f-k array with the inverse of the f-k transform of the multiple reflections.

One way of carrying out the invention is to make a normal moveout correction with the apparent velocity of the multiple reflections. This aligns the multi-
70 ple reflections in the CDP set. By stacking the CDP set after correction for normal moveout, an estimate is obtained of the multiple reflections. This estimate is successively time shifted by varying times to produce seismograms representing a CDP set of the
75 multiple reflections. The multiple reflection CDP set is converted into an f-k array and the inverse of this array is obtained. This is an array of samples which are inversely proportional to the amplitude of the multiple reflections as a function of frequency and
80 wave number.

The seismic section from which multiple reflections are to be filtered is also converted into an f-k array. This f-k array is filtered by weighting all samples in it by the corresponding samples in the
85 inverse multiple reflection f-k array. In this manner, multiple reflections are suppressed. When the filtered f-k array is converted into a normal X-T array, an enhanced representation of the earth's formations without multiple reflections is obtained.
90 Further features and advantages of the invention are disclosed below with reference to the drawings in which:

Figure 1 is a flow sheet depicting the filtering process;
95 *Figure 2* depicts a set of CDP seismograms, and the f-k transform of that set;

Figure 3 depicts the CDP set of Figure 1 after correction for normal moveout with the apparent velocity of the multiple reflections;
100 *Figure 4* depicts an estimate of multiple reflections obtained by stacking the CDP set of Figure 3;

Figure 5 depicts a set representing the multiple reflections which has been obtained by successively time shifting the estimate of Figure 4;
105 *Figure 6* is an example of sets of CDP seismograms;

Figure 7 shows sets of seismograms representing the multiple reflections in the sets of Figure 6;

Figure 8 depicts the sets of Figure 6 after multiple
110 reflections have been filtered out in accordance with the present filtering process;

Figure 9 is an example of a field section which has been processed and stacked with standard procedures; and
115 *Figure 10* depicts the same seismograms after the f-k multiple reflection filtering and stacking of the present filtering process.

The filtering process shown in Figure 1 operates on sets of common depth point seismograms 11.
120 Such CDP sets are depicted in Figure 2, wherein the X direction depicts distance along a line of exploration and the T direction depicts time after the pulse of seismic energy producing the seismograms. In accordance with CDP techniques, the seismograms
125 in each set contain reflections of seismic energy from the same reflecting points. The reflections from subsurface interfaces occur in the sets along approximately hyperbolic arcs such as 12, 13 and 14 in Figure 2. The time of a reflection in any set is given
130 by the well known expression:

$$T^2 = T_0^2 + X^2/V^2$$

5   where T_0 is the time of the reflection at the zero
offset trace, X is the horizontal distance between
source and detector, and V is the acoustic velocity
characteristic of the earth. The multiple reflections
10   line up along different hyperbolic arcs such as 15, 16
and 17 in Figure 2. Such a seismic set is generated in
the field and stored on magnetic tape or in a digital
computer as an array of seismic samples represent-
ing the amplitude of the seismic reflections as a
15   function of time T and distance X along the line of
exploration. The samples in such an array are
designated S(X,T). Fourier transforms which convert
such an array into an array of amplitude as a
function of frequency and wave number are known.
20   Such an f-k array is shown at the right side of Figure
2. The digital samples are denoted S(f,k).
    As a first step toward obtaining seismograms
representing only multiple reflections, the CDP sets
11 are corrected for normal moveout with the
25   apparent velocity V_m of the multiple reflections. This
step is indicated at 18 in Figure 1. It produces the
seismic set which is depicted in Figure 3. In this set,
the multiple reflections have been aligned so that
they appear on the straight lines 19, 20 and 21. When
30   such a set is stacked, an estimate of the multiple
reflections is obtained. The step of stacking is
indicated at 22 in Figure 1.
    The resulting estimate of the multiple reflections is
shown in Figure 4 where the stacked seismogram
35   has the multiple reflections 23, 24 and 25. This
estimate is converted into a CDP set representing the
multiple reflections. The time variant time shift
indicated at 26 in Figure 1 performs this operation.
This is merely a time shifting operation which is the
40   reverse of the normal moveout operation indicated
at 18. That is, the apparent multiple velocity is used
to determine the time shift to be successively
applied to the estimate of Figure 4 to produce the set
representing multiple reflections in Figure 5. Figure 5
45   depicts the estimates 27, 28 and 29, each with
successive time shifts, but of course there will be
many more seismograms in the typical CDP set.
    Figure 5 also depicts the f-k transform of the set
representing the multiple reflections. The set repre-
50   senting multiple reflections at the left in Figure 5 is
represented by an array of digital samples represent-
ing amplitude as a function of time and distance. The
digital samples in such an array are designated
M(X,T) where each digital sample represents an
55   amplitude for a particular value of X and T. The right
hand side of Figure 5 depicts an array of digital
sample for each frequency and wave number value
in the array. The digital samples are designated
M(f,k) where each digital samples represents the
60   amplitude for a particular value of frequency and
wave number.
    The step of performing the f-k transform on the set
representing multiples is indicated at 30 and 30A in
Figure 1. This step can be carried out by many
65   conventional Fourier transforms, but the Cooley-

Tukey transform described in Cooley, J.W.; Tukey,
J.W., "An Algorithm for Machine Calculation of
Complex Fourier Series", *Mathematical Computa-
tion*, Vol. 19, 1965, pp. 297-301 is particularly suitable
70   for use. The adaptation of the transform for use in
seismic processing is more fully described in our
co-pending application referenced above and incor-
porated by reference. That application also describes
in more detail the transform into a real part,
75   indicated at 30, and the transform into an imaginary
part, indicated at 30A.
    In accordance with the present invention, the
inverse of the array M(f,k) representing multiples, is
obtained in order to determine the weights of the
80   filter which is to be applied. This step of generating
the inverse is indicated at 31 in Figure 1. An inverse
operation performed on an f-k array is carried out by
division. That is, the weights, W(f,k) of the filter are
the inverse of the multiple reflection section. Stated
85   in another way,

$$W(f,k) = 1/M(f,k) = 1/(RM + iIM)$$

90

    In the foregoing, RM represents the real part of the
weighting function and ilm represents the imaginary
part. In co-pending application No. 8125268 (Mobil
Case F-0343) the multiples are removed by a reject
95   filter which operates only on the absolute value of
the transform of the seismic section. The filter of the
present process operates on the complex real and
imaginary parts of the f-k transform of the seismic
section. The operation is simplified by multiplying
100 both the numerator and the denominator by RM -
ilM. This produces:

$$W(f,k) = RM/(RM^2 + IM^2) - iIM/(RM^2 + IM^2)$$

105

    The foregoing consists of two parts. One contains
the coefficients for filtering the real part of the
seismic section. The other contains the coefficient
110 for filtering the imaginary part of the seismic section.
The real coefficients are applied to the filter 32. The
imaginary coefficients are applied to the filter 33.
    The seismic section to be filtered is converted into
an f-k array by the real f-k transform 34 and the
115 imaginary f-k transform 35. Again, these f-k trans-
forms may be performed in accordance with the
procedure described in co-pending application No.
8125268 (Mobil Case F-0343). The real part of the
array S(f,k) is applied to the filter 32 and the
120 imaginary part is applied to the filter 33. The filters
32 and 33 weight each of the samples in the array
S(f,k) by a factor which is inversely proportional to
the amplitude of the corresponding sample in the f-k
transform of the multiple reflections. In implement-
125 ing the filtering in a digital computer, the simplest
procedure is to multiply each filter coefficient, from
the inverse multiple reflection f-k array, by the
corresponding sample in the seismic section f-k
array. Digital filtering techniques are well known.
130 The filtering has the effect of suppressing multiple

reflections. The filtered arrays are transformed back into normal X-T arrays by th step indicated at step 34. This produces a section having enhanced representation of the earth's formation without the multi-
5 ple reflections.
Examples of the operation of the present invention are shown in the seismograms of Figures 6-10. Figure 6 depicts field seismograms in ten CDP sets. This corresponds with the idealized set shown in
10 Figure 2. After processing by the steps 18, 22 and 26 of Figure 1, these field seismograms have the appearance of Figure 7. Figure 7 shows sets representing only multiple reflections. These sets are converted into an f-k array by the steps 30 and 30A of
15 Figure 1 and the weighting coefficients of the filter are determined by the inverse operation depicted at 31 in Figure 1.
Figure 8 shows seismic sets which have been transformed into an f-k array, filtered by the steps 32
20 and 33 of Figure 1 and then transformed back into an X-T array. Good multiple suppression has been obtained.
Figures 9 and 10 are further examples of the effectiveness of the present invention. Figure 9
25 shows a seismic section which has been stacked after standard processing. Note the strong multiple reflection indicated at 35, approximately 3.15 seconds record time. Also there is severe ringing caused by multiple reflections in the portion of the
30 record indicated at 36, approximately 4.4 through 6.0 seconds of record time.
Figure 10 is the same seismic section which has been processed and stacked by the same processing except that the f-k multiple filtering of the present
35 invention has been applied. Note that the multiple reflection at 3.15 seconds has been effectively suppressed. Also, the ringing between 4.4 and 6.0 seconds has been greatly improved.

40 CLAIMS

1.   A method of filtering multiple reflections from seismograms representing the earth's formations comprising:
45   transforming seismograms representing the amplitude of seismic reflections as a function of time and distance along a line of exploration into an f-k array representing the amplitude of the reflections as a function of frequency and wave number;
50   generating the inverse of the f-k transform of the multiple reflections;
   filtering the f-k array by weighting all the samples in the array with the inverse of the multiple reflections; and
55   generating from the filtered array a seismic record having an enhanced representation of the formations with suppression of the multiple reflections.
2.   A method according to claim 1 in which the inverse of the f-k transform of the multiple reflec-
60 tions is generated by:
   correcting the seismograms for normal moveout with the apparent velocity of the multiple reflections so as to align the multiple reflections;
   transforming the corrected seismograms with
65 aligned multiple refl ctions into an f-k array; and

determining the inverse of the f-k array.
3.   A method according to claim 2 in which the normal moveout correction is made by time shifting common depth point sets with the apparent velocity
70 of the multiple reflections to align the multiple reflections, and the transforming is made by stacking the normal moveout corrected common depth point sets to produce an estimate of the multiple reflections, successively time shifting the estimate of
75 multiple reflections by varying times to produce a set representing the multiple reflections, and transforming each set into an f-k array.
4.   A method according to any of claims 1 to 3 in which the filtering is performed by weighting each
80 sample in the f-k array by a factor which is inversely proportional to the amplitude of the corresponding sample in the f-k transform of the multiple reflections.